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Water-Assisted Femtosecond Laser Pulse Ablation of High Aspect Ratio Holes

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Abstract

Two novel techniques to enhance hole drilling in a silicon using a femtosecond laser, is presented. Firstly, the sprayed thin water layer has been used in an ablation region. Sprayed water removes the ablation debris and enables more efficient pulse energy transition into ablated material than in the air ambient. Secondly, the diffractive optical element (DOE) that generates into its far field 5x5 hole matrix at single irradiation, is used. By using the DOE instead of single hole drilling it is possible to ablate several holes simultaneously. Both of these techniques enhance the femtosecond ablation rate significantly.

Keywords: ablation; micro-structures; diffractive optics

1. Introduction

The high aspect hole drilling into silicon has been investigated extensively, because they have various applications in many fields, e.g. micro-electro mechanical systems (MEMS), micro-fluidics, optics and photonics [1]. Added to various lithographical methods high aspect holes in silicon can be made using lasers. In a laser ablation there have been several experimental studies to test an influence of different environments on ablation in order to speed up the ablation process [2-3]. Ablation experiments have been made in both liquid and gas environments [4]. Added to basic understanding of the ablation mechanism, these experiments have been done to speed up the ablation rate and to enhance surface smoothness of the holes input and edges. Usually, these goals can be achieved if the amount of debris during ablation is reduced. If debris is not removed during the ablation process, it usually attaches to the material and in many cases cannot be removed afterwards. This attached debris can also block energy transfer into the material itself. If debris is not removed, pulse energy is partly transferred into debris instead of material processing. So a removal of the debris during the ablation process is beneficial.

In the case of the ablation of macro-size structures using nanosecond range long pulses, water has been used beneficially to enhance the ablation rate and to reduce an amount of debris in various ways [2,3,5]. In these studies it has been seen that in the case of the thick water layer, the ablation rate is less and the smoothness of the crater is rougher than in air ambiance. This is partly because the shape of the pulse is distorted and energy is absorbed by the

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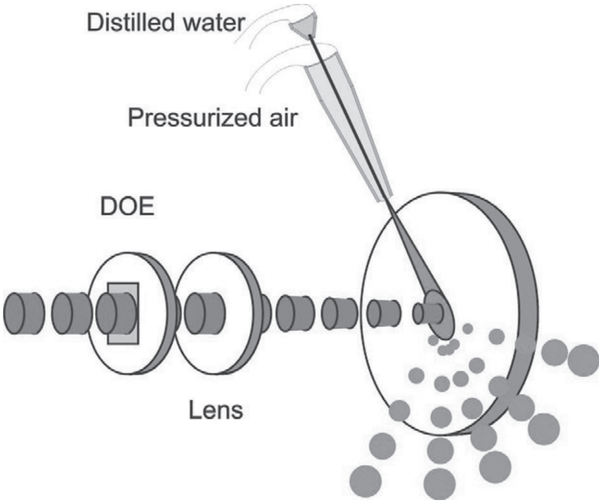
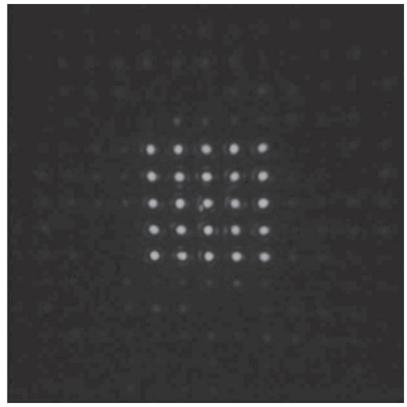


(a)



(b)

Figure 1. Schematics of the ablation setup (a). Fine water film is generated on the sample next to the ablation spot using pressurized air. In (b) is shown CCD-camera picture of the DOEs far-field image used in the experiments. DOE is illuminated using a femtosecond laser and by using magnification imaging system, the far-field image of the DOE is generated onto the screen.

thick water film. This is not a problem, if water film is thin enough (in a range of the incident wavelength), because in this case it enhances lights coupling into matter [6]. Water-assisted laser ablation, using femtosecond pulses, has been done in the thick water layer [7], under flowing water [8] and with sprayed water film [9,10]. In these papers only holes with several tens of microns diameter are considered and secondly the high aspect ratio holes are not considered (aspect ratio is the depth of the hole divided by the diameter of the hole). With nanosecond pulses there have been some ablation studies where high aspect ratio holes are fabricated, but in the case of long pulses the heating of the sample is causing several problems like cracking of the silicon and deforming of the holes [11].

To achieve the small size of the hole and to avoid silicon cracking, laser drilling requires relatively small energies. Therefore ablations presented in this paper are made by applying a flexible method based on diffractive optical element (DOE) [12,13], so that energy of the ultrashort laser can be utilized more effectively. In this method, instead of irradiating a hole by a hole, several holes are ablated simultaneously. The amount of the holes that can be ablated simultaneously depends on the laser energy at your disposal and can be controlled by DOE design. Size of the ablated holes can be controlled either by the design of DOE or by using imaging lenses with different focus lengths.

In this paper is presented the femtosecond laser ablation of holes in micrometer range with a sprayed thin water layer on the silicon surface. These results were compared to the similar ablations which were made in an air ambient. By using water-assisted ablation, the ablation rate was increased and it was possible to obtain deeper and better quality holes than in the air ambient.

2. Experimental

Quantronix Intergra C-3.5 mJ, that provides 130 fs and 780 nm central wavelength pulses with 3.5 mJ energy at 1 kHz repetition rate, is used in the experiments. In Figure 1. (a) is shown the schematic of the ablation setup that consisting DOE and imaging lens. Mixture of pressurized air and distilled water are used for the generation of thin water film onto ablation spot. Spatially and temporally Gaussian shape beam is directed through a 2-level on-axis phase modulating DOE that creates 5x5 spots into its far-field. The number of spots that DOE generates can be selected in design, but usually the efficiency and uniformity of the diffraction pattern are worse when increasing the number of spots. This phase element was designed using a commercial program, which uses Iterative Fourier Transform Algorithm (IFTA) for optimization [14]. DOE was fabricated using standard e-beam lithography and etching. In Figure 1. (b) there is CCD-camera image of the fabricated DOEs far-field intensity distribution. After

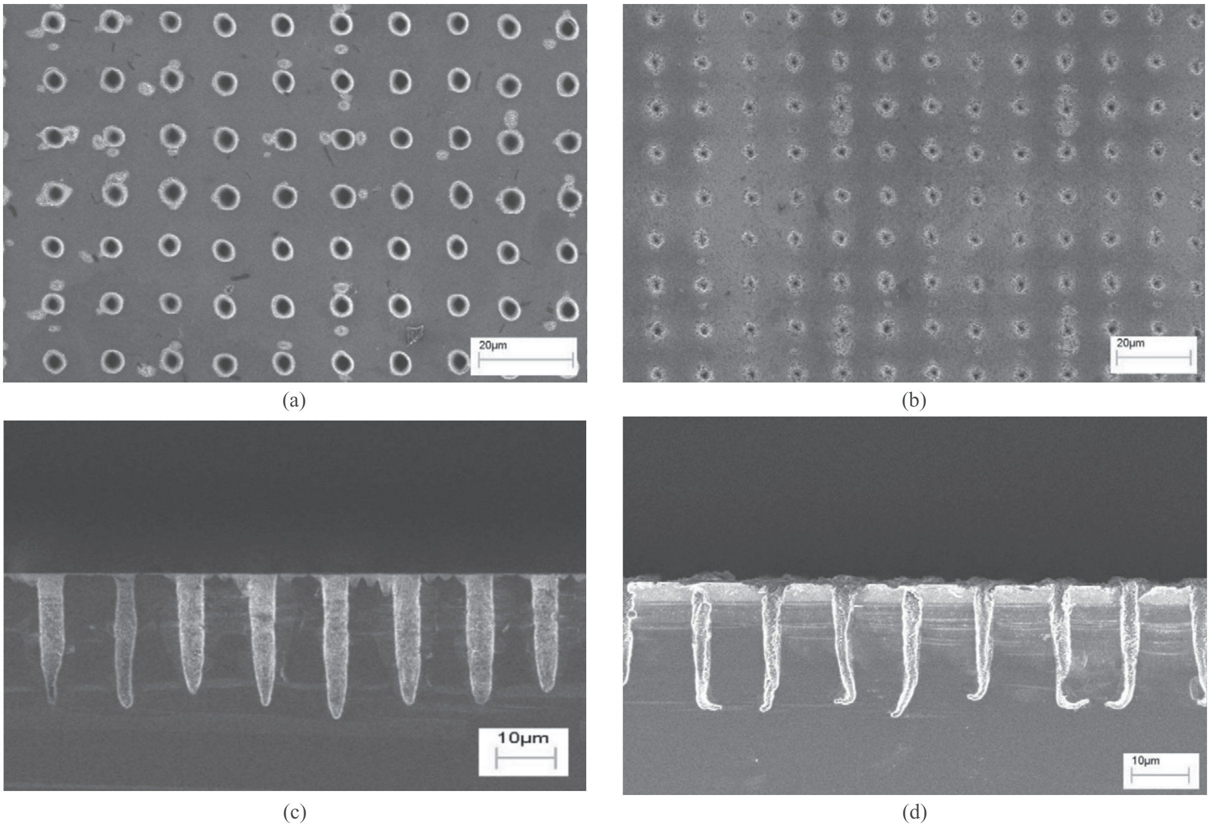


Figure 2. The SEM Figureures of the ablations made in silicon with (a), (c) and without (b), (d) water spray. (a) and (b) are made with 1000 pulses and 1.2J/cm^2 fluence. (c) is made using 500 pulses and 2.9J/cm^2 fluence, respectively (d) is made using 1000 pulses and 5.8J/cm^2. (a)-(b) are taken from the top of holes and (c)-(d) from the side cut of the same holes, respectively.

this phase element, pulses are guided through a lens that creates DOE's far-field image into its focus. Size of the far-field image in a focus can be changed either by design or changing the lens focal length.

The depth and quality of the drilled holes are studied as a function of the fluence and pulse number in silicon. The holes were ablated both with and without water spray. Holes are drilled with two different focusing lenses, with f = 100 mm and f = 25 mm focal lengths, in order to ablate holes with a different diameter. DOE was designed so that with 100 mm focal length lens we can ablate holes with 16μm diameter and with 25 mm focal length lens respectively holes with a diameter of 4 μm.

3. Results and Discussion

In Figure 2. is shown the SEM-images from comparative ablation made with (left) and without (right) a thin water film using 25 mm focal length lens. The holes shown in the images taken from the top of the sample are made using 1000 pulses and 1.2 J/cm^2 fluence. The holes in side cut image (c) is made with 500 pulses and 2.9 J/cm^2 fluence and (d) using 1000 pulses and 5.8 J/cm^2. The depth of holes are both approximately 25 μm, although (d) is not only made with two times higher fluence, but also with two times higher pulse number than (c). In Figure 3. is collected a graph of ablation depths as a function of fluences, in a case of 25 mm focal length lens made using with and without water spray. As this Figureure shows, the water-assisted ablation is clearly more efficient than ablation in air atmosphere. With water, the ablation rate is about two times faster than without it. Reason for this is the removal of the ablation debris during the drilling process. When there is no thin water spray to collect and transport the debris away from the processing area, the ablation debris is blocking the energy transition into the ablation process itself. Debris scatters and absorbs the incoming pulses and therefore drilling is not so efficient. When water is used, it removes debris continuously away from the holes and therefore drilling process is equally efficient with

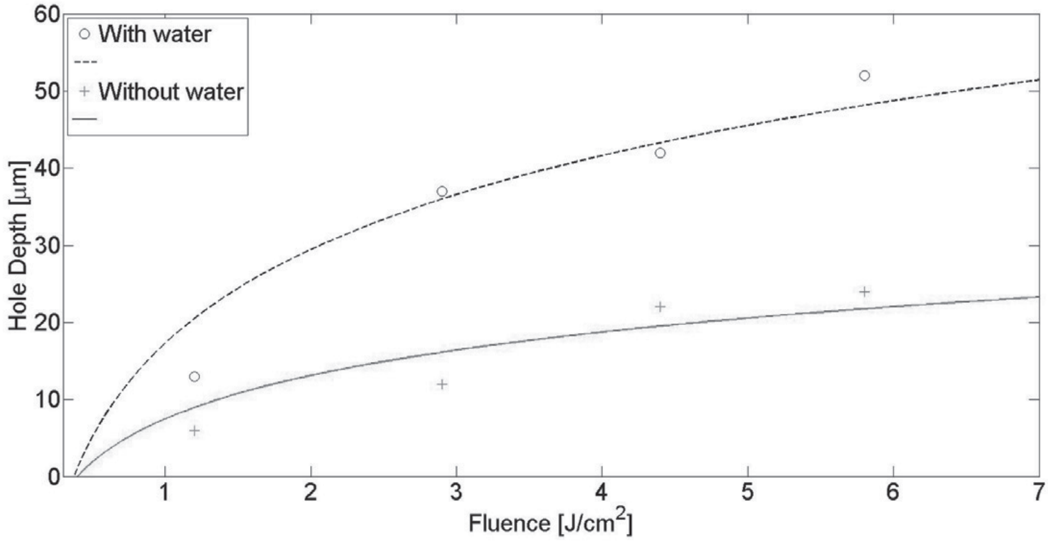


Figure 3. The measured ablation depths of the holes as the function of fluence with (circle) and without (cross) sprayed thin water film. Dashed line is logarithmic fitting for hole ablations made using water and solid line for ablations made without water. The results are obtained using 1000 pulses.

following pulses. Scattering caused by debris is also inflicting the shape of the hole, which can be seen in Figure 2. (d). Here the debris is causing the curving of the ablated holes, which is not observed in an ablations made with the thin water film, Figure 2. (c). When the hole start curving like that no amount of subsequent pulses can make it any deeper. In this case the water-assisted ablation is not only more efficient, but it also enables the ablation of deeper holes with a higher aspect ratio.

For applied pulse numbers and fluences, the maximum aspect ratio obtained with 25 mm focal length lens, was approx. 13, using water-assisted ablation. With higher values of pulse number or/and fluence the aspect ratio could have been increased at the expense of the entrance quality of the holes. In the air atmosphere, the maximum aspect ratio was approx. 6 and the quality of these holes was rough compared ones made with water. Using the longer focal length lens (f = 100 mm) we have been able to ablate holes with the aspect ratio more than 23. In this case holes were drilled through the silicon sample and therefore maximum aspect ratio values could not have been determined. Without water and the lens with f = 100 mm maximum obtained aspect ratio was approx. 10.

In the experiment it was also seen that by applying the thin water layer, it is possible to ablate better entrance quality holes, which can be seen in Figure 2. (a) and (b). In the case of the water ablated holes, the sample surface surrounding the holes is smooth and debris free. The holes ablated in the air have not only larger heat-affected zone around the holes, but also the area between the holes is filled with debris. In this case subsequent cleaning of the debris was tried using ultrasound cleaning in acetone, but no changes were observed in the amount of debris.

Note, that only a small portion of the available laser energy was used in the experiments. From the results shown in Figureure 3 we can estimate the amount of holes that can be simultaneously ablated using the maximum energy of the laser assuming that we have suitable DOE at our disposal. Using fluence of 6 J/cm^2 and 1000 pulses resulting the depth of 50 μm for the holes of 4μm diameter up to 4000 holes could be ablated simultaneously using pulses with 3.5 mJ of energy. This result corresponds to the ablation rate of 4000 holes per second.

4. Conclusions

In this paper it has been shown that by using the water-assisted ablation it is possible to ablate micrometer range high aspect ratio holes in a silicon using a femtosecond laser. By applying thin water layer on the processed surface holes can be drilled more efficiently, faster and with the better quality than in air atmosphere. Reason for this is that during the ablation process, water removes the ablation debris immediately away from the processing area. If the debris is not removed from the ablation region during ablation, it blocks the energy transition into the matter. It also scatters incoming light causing the deformation of the hole shape. Water also cleans the surrounding area of the ablation from the debris and subsequent cleaning of the sample is not needed.

Acknowledgements

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